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Abstract. We have analyzed shear wave splitting recorded by portable and permanent broadband and long-period stations located in the eastern United States. Teleseismic shear waves (*SKS*, *SKKS*, and *PKS*) were used to retrieve the splitting parameters: the orientation of the fast wave polarization plane ϕ and the delay time δt. In total, 120 seismic events were processed, allowing for more than 600 splitting measurements. Within the Appalachians, stations located in the western (external) part are characterized by $\delta t \approx$ 1s and ϕ trending N50°-70°E in the south and central regions and N30°-40°E in the north, closely following the trend of the orogenic belt in these areas. The transition region between north and central is characterized by $\delta t \approx$ 1 - 1.3 s and by E-W trending ϕ that are at a high angle to the regional geologic trend. Measurements at two stations located in the eastern (internal) part of the belt indicate very weak anisotropy. The large-scale pattern of anisotropy is not consistent with that predicted for simple asthenospheric flow beneath the plate. Splitting along the southern and eastern margins of the continent is consistent with that expected for Grenvillian deformation, an alternative model of asthenospheric flow around the cratonic keel cannot be ruled out. Within the cratonic core, the correlation between δt and lithospheric thickness suggests a lithospheric anisotropy. Smaller-length-scale variations also argue for a significant contribution of lithospheric structures. The fabric responsible for shear wave splitting may have formed during tectonic episodes that affected the eastern United States, i.e., the Grenville and Appalachian orogenies and the subsequent rifting of the North Atlantic Ocean. Our observations in the western Appalachians suggest that the anisotropy may be preserved since the Grenvillian orogeny. The absence of detectable splitting in the two stations in the eastern Appalachians is attributed to the igneous intrusions related to the Atlantic rifting. The measurements in the transition between the northern and central southern Appalachians, constitute an intriguing anomaly, whose E-W ϕ have little obvious relation to the regional surface geology. We suggest two possible causes: (1) the local dominance of asthenospheric flow, motivated by the proximity of a pervasive low-velocity anomaly and (2) lithospheric deformation in a transcontinental strike-slip fault zone active during the Appalachian collision.

Introduction

Core shear phases (such as *SKS*, *SKKS* or *PKS* phases) are generated through a *P*-to-*S* conversion at the core-mantle boundary. They are initially radially polarized and reach the surface at near normal incidence angle. When they cross a seismically anisotropic layer along their path from the core-mantle boundary to the Earth's surface, these phases are split in two orthogonally polarized waves that travel at different velocities. At the Earth's surface, the split waves are characterized by the differences in arrival times (δt) and by the orientation of the fast polarization direction (ϕ). Because these two parameters are dependent on both the intrinsic anisotropy and the thickness of the anisotropic layer, the depth at which splitting occurs cannot be directly determined.

From seismological and petrophysical evidence, it is nevertheless widely accepted that the splitting of teleseismic shear waves occurs in the most external layers of the Earth, the asthenosphere, and/or the lithosphere. Combining seismological observations and high-pressure mineral physics experiments, *Meade et al.* [1995] explain why the lower mantle appears to be nearly isotropic. This may be due to the absence of lattice preferred orientation (LPO) in (Mg,Fe)SiO_3 perovskite which is nevertheless intrinsically anisotropic. An important seismological argument supporting anisotropy located in the external layers of the Earth is that in numerous experiments, the splitting parameters ϕ and δt display significant variations over a few tens of kilometers [e.g., *Hirn et al.*, 1995; *Savage and Silver*, 1993] that are clearly incompatible with deep sources of anisotropy. On

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the other hand, crustal anisotropy has been observed at stations above intracrustal seismic events and generally attributed to the microfracturing controlled by the state of stress in the upper crust [*Kaneshima et al.*, 1988; *Peacock et al.*, 1988]. Recent investigations on splitting of *P*-to-*S* converted phases at the Moho discontinuity have nevertheless provided more accurate insights on crustal anisotropy [*Herquel et al.*, 1995; *McNamara and Owens*, 1993]. Delay times up to 0.2-0.3 s are observed and are consistent with values predicted from rock physics [*Barruol and Mainprice*, 1993; *Ji and Salisbury*, 1993]. As a result, it is reasonable to conclude that the crust can only slightly contribute ($\leq$ 0.3 s) to the observed delay times [see *Silver*, 1996].

An upper mantle origin of teleseismic shear wave splitting is therefore very likely, and LPO in anisotropic minerals, especially of olivine which displays a strong intrinsic elastic anisotropy, has been recognized as the main source of this deep anisotropy [*Mainprice and Nicolas*, 1989; *Nicolas and Christensen*, 1987]. The relatively simple relationship between splitting parameters and the crystallographic fabric of mantle rocks has turned shear wave splitting into a useful tool to investigate upper mantle deformation [*Silver*, 1996]. It remains controversial, however, whether the observed anisotropy is primarily an effect of the present-day asthenospheric flow beneath an isotropic moving plate [*Vinnik et al.*, 1992], is due mainly to 'fossil' lithospheric fabric formed during past tectonic events [*Silver and Chan*, 1991], or results from a combination of various processes.

Upper mantle xenoliths from kimberlites [*Mainprice and Silver*, 1993] and alkaline basalts [*Ji et al.*, 1994] demonstrate that mineral phases in the continental lithospheric mantle systematically display lattice preferred orientation and therefore are seismically anisotropic. In most cases, maximum shear wave anisotropy ranges from 3 to 5% and is generally found for waves propagating in a direction nearly normal to the lineation in the foliation plane. The related fast split shear wave is polarized in a plane parallel to the lineation. Using these data, the most commonly observed δt values (~1 s) may be explained for a lithosphere of "normal" thickness (~100 km) by the existence of a steeply dipping foliation and a moderately plunging lineation in the lithospheric mantle. However, because xenoliths are detached from their source area, they do not carry any information about the orientation of the structural reference frame (foliation plane, lineation direction). This information must be obtained from other sources. Combining body and surface waves, *Gaherty and Jordan* [1995] constrained the depth origin of the anisotropy beneath Australia to be in the uppermost 200 km, i.e., mostly in the lithospheric mantle. Finally, a good correlation of splitting parameters with surface geology [*Barruol and Souriau*, 1995; *Helffrich*, 1995; *Silver*, 1996; *Silver and Kaneshima*, 1993] is generally found and supports an anisotropy mainly due to fossil tectonic fabric in the subcrustal lithosphere.

Compared to the oceanic case, for which the asthenosphere is well characterized and clearly controls the development of the lithospheric structure [e.g., *Tommasi et al.*, 1996], the continental lithospheric upper mantle probably displays a much more complex structure that reflects its long history. The development of a sheared layer beneath a moving lithospheric plate is physically reasonable; however, the lack of unambiguous samples from the subcontinental asthenosphere precludes petrophysical investigations of the intrinsic seismic anisotropy similar to those performed for the lithospheric mantle. Interpretation of splitting observations in term of asthenospheric flow was presented for the Kaapval craton, for instance by *Vinnik et al.* [1995], but they did not consider the possible role of geology and the evidence of crystallographic preferred orientation systematically found in kimberlite nodules [*Boullier and Nicolas*, 1975; *Mainprice and Silver*, 1993]. Models involving small-scale convection [*Makeyeva et al.*, 1992] have been invoked to account for lateral variations of the observed anisotropy occurring over short distances. Perturbations of the asthenospheric flow around topographic irregularities of the lithosphere-asthenosphere boundary have been also proposed by *Bormann et al.* [1996] to explain the variation in orientation of the fast split shear wave in central Europe.

Shear wave splitting measurements have been performed using data recorded in various geological/tectonic environments by permanent and portable networks: Archean shields [e.g., *Silver and Kaneshima*, 1993; *Vinnik et al.*, 1995], mountain belts of various ages [e.g., *Barruol and Souriau*, 1995; *Makeyeva et al.*, 1992; *McNamara et al.*, 1994], strike slip zones [*Russo et al.*, 1996; *Savage and Silver*, 1993], and present-day subduction zones [e.g., *Kaneshima and Silver*, 1994; *Russo and Silver*, 1994] and rifts [*Gao et al.*, 1994; *Sandvol et al.*, 1992]. Although significant progress has been made, no single tectonic process can account for all of the observations; contribution of various processes is required [*Silver*, 1996; *Vauchez and Barruol*, 1996].

In this paper, we present results of shear wave splitting measurements in the eastern United States. Because the North American lithosphere was built since Archean times through successive tectonic events involving terrane accretions, mountain building, ocean opening and closure, the eastern United States represents a particularly interesting area to address issues such as the age and location of anisotropic structures responsible for splitting. This provides an opportunity to analyze upper mantle anisotropy beneath domains of different ages and tectonic histories. The major drawback of this area is the large-scale parallelism between the present-day absolute motion of the North American plate (~N65°E), and the trend of various major tectonic features, such as the Appalachian and Grenville belts, or the Iapetus and Atlantic initial rifts. In several places this precludes an unambiguous interpretation of shear wave splitting parameters. We first present the observations and analyze the results. Then, considering our observations together with other geophysical and geological evidence, we discuss the lithospheric and/or asthenospheric origin of anisotropy, and the possible contribution of the various tectonic episodes.

Observations and Data Processing

Experiment

Seismic events used for splitting measurements were recorded by 23 portable and permanent stations with coordinates listed in Table 1. Three portable broadband stations from the Carnegie Institution of Washington (DTMR, CSMR and BCMR) were running for 18 months along a transect roughly normal to the structural trend of the Appalachians in the Maryland area. Data recorded by three-component broadband permanent stations from GEOSCOPE (WFM), the Incorporated Research Institutions for Seismology (CCM and HRV), and the Global Digital Seismic Network (SCP, RSNY and RSCP) were also analyzed. Finally, we used almost three years of long-period data from the U.S. National Seismic Network (USNSN) stations located in the eastern United States.

The stations are in lithospheric domains characterized by various geologic histories (Figure 1): CBKS, CCM, FVM, JFWS, and EYMN are installed on the cratonic nucleus of the North

Table 1. Stations Location and Averaged Splitting Results

					Weighted Mean				Stacking of the Splitting Results (Wolfe and Silver, submitted manuscript, 1996)				
Station	Latitude °N	Longitude °W	Elevation, m	Source	ϕ, deg	$\sigma\ \phi$, deg	δt, s	$\sigma\ \delta t$, s	ϕ, deg	$\sigma\ \phi$, deg	δt, s	$\sigma\ \delta t$, s	Number of Measurements
JELA	31.785	92.015		LRSM*	83	—	1.10	—	—	—	—	—	—
EUAL	32.779	87.874		LRSM*	92	—	0.80	—	—	—	—	—	—
BCMR	39.510	77.710	165	Carnegie	73.	7.	1.06	0.27	73.	14.	1.05	0.45	2
BINY	42.199	75.986	498	USNSN	101.	5.	0.85	0.12	108.	7.	0.65	0.08	8
BLA	37.211	80.421	634	USNSN	58.	8.	1.12	0.05	70.	4.	1.00	0.10	6
CBKS	38.814	99.737	677	USNSN	42.	6.	0.61	0.09	44.	7.	0.50	0.08	7
CBM	46.933	68.121	250	USNSN	39.	4.	1.15	0.06	34.	2.	0.95	0.08	9
CCM	38.056	91.245	223	IRIS	34	3.	0.73	0.06	—	—	—	—	11
CEH	35.891	79.093	152	USNSN	104.	13.	1.11	0.20	—	—	—	—	2
CSMR	39.690	77.970	232	Carnegie	50.	4.	0.98	0.13	48.	5.	0.90	0.13	3
DRLN	49.250	57.500		Bostock⁺	29	—	0.85	—	—	—	—	—	—
DTMR	38.960	77.060	0.0	Carnegie	66.	15.	0.75	0.33	—	—	—	—	1
EYMN	47.946	91.495	475	USNSN	52.	2	1.38	0.05	57.	1.	1.35	0.05	23
FVM	37.984	90.426	310	USNSN	42.	5	0.83	0.08	34.	3.	0.50	0.08	10
GOGA	33.411	83.467	150	USNSN	144.	5.	1.15	0.20	—	—	—	—	1
HRV	42.506	71.558	180	IRIS	86.	5.	0.99	0.11	89.	6.	0.65	0.10	11
JFWS	42.915	90.249	318	USNSN	46.	11.	0.84	0.26	39.	11.	0.60	0.18	3
LBNH	44.240	71.926	367	USNSN	83.	8.	1.34	0.30	84.	20.	0.85	0.38	2
LSCT	41.678	73.224	318	USNSN	83.	3.	1.38	0.13	87.	3.	1.00	0.15	12
MCWV	39.658	79.846	280	USNSN	67.	12.	1.18	0.07	78.	4.	1.20	0.20	3
MIAR	34.546	93.573	207	USNSN	89.	6.	1.15	0.14	96.	6.	0.70	0.10	8
MYNC	35.074	84.128	550	USNSN	63.	3.	1.38	0.14	63.	2	1.50	0.13	10
OXF	34.512	89.409	101	USNSN	61.	3.	1.55	0.13	59.	1	1.55	0.05	4
RSCP	35.600	85.590	481	USNSN	59.	6.	0.75	0.15	—	—	—	—	—
RSNY	44.548	74.530	396	GDSN	74.	5.	0.90	0.15	—	—	—	—	—
SCP	40.795	77.865	352	GDSN	64.	4.	0.83	0.05	67.	2.	0.70	0.05	7
SSPA	40.636	77.888	158	IRIS	70.	5.	1.15	0.28	—	—	—	—	1
WFM	42.610	71.490	88	Geoscope	96.	4.	1.10	0.22	95.	5.	1.05	0.28	4
WMOK	34.738	98.781	486	USNSN	109.	4.	0.77	0.07	109.	3.	0.70	0.05	12
YSNY	42.476	78.538	628	GDSN	77.	5.	1.06	0.08	82.	3.	1.10	0.10	5

* Data kindly provided by E. Sandvol and J. NI.

⁺M. Bostock and J. Cassidy (unpublished results, 1996).

Mean results were calculated weighting individual splitting measurements by theirs 95% confidence intervals [*Silver and Chan*, 1991] but also by stacking the 95% confidence intervals in the ϕ-δt domain (*C. Wolfe and P.G. Silver*, Submitted manuscript, 1996). Both results are shown here allowing the comparison to be done. The number of non null measurements taken into account for this average is shown in the last column. We show Figure 6 that larger is this number better constrain is the result. For this reason, the final results shown Figure 8 are sorted in two classes: the best constrained (in black), derived from more than five independent measurements and the others, in gray.

American plate [*Hoffman*, 1989]. This stable craton is made up of Archean to middle Proterozoic rocks. Because most of the craton is blanketed by sediments, the crustal structure beneath most of these stations is not directly observable. Only indirect observations, for instance, aeromagnetic or gravimetric surveys, may provide some insights into basement structures. Stations MIAR, OXF, RSCP, YSNY, BINY, and RSNY are located on the Grenville belt and the remaining in the Appalachians.

Event Selection

Seismic events were selected and extracted using the U.S. Geological Survey (USGS) Preliminary Determination of Epicenters. For shear wave splitting measurements, we used around 120 events of magnitude greater than 5.7 (generally > 6.0) at teleseismic distances in the range 85 to 180° (Table A1[1]) on which about 600 individual teleseismic shear wave splitting measurements were carried out (Table A2[1]). Phase arrivals were calculated using the 'IASPEI91' tables [*Kennett*, 1991]. Only events with good signal/noise ratio for the *S* phases were kept for measurements. Most events on which we obtained good measurements have in fact a m_b> 6.2 and are at distances between 85° and 110°.

Splitting Measurements

We measured shear wave splitting using *SKS*, *SKKS*, and/or *PKS* waves, depending on the event distance and obviously on the quality of the original seismograms. We used the algorithm described by *Silver and Chan* [1991] that determines the couple of anisotropy parameters (ϕ and δt) that best remove the energy on the transverse component of the selected phase. This method assumes that the seismic anisotropy is homogeneous in a single horizontal layer. Some unexpected variations or apparent scattering of the splitting parameters may result from the fact that

[1] Supporting data [Tables A1 and A2] are available on diskette or via Anonymous FTP from kosmos.agu.org, directory APEND (username=anonymous, Password=guest). Diskette may be ordered from the American Geophysical Union, 2000 Florida Avenue, N.W., Washington, D.C. 20009 or by phone at 800-966-2481; $15. Payment must accompany order.

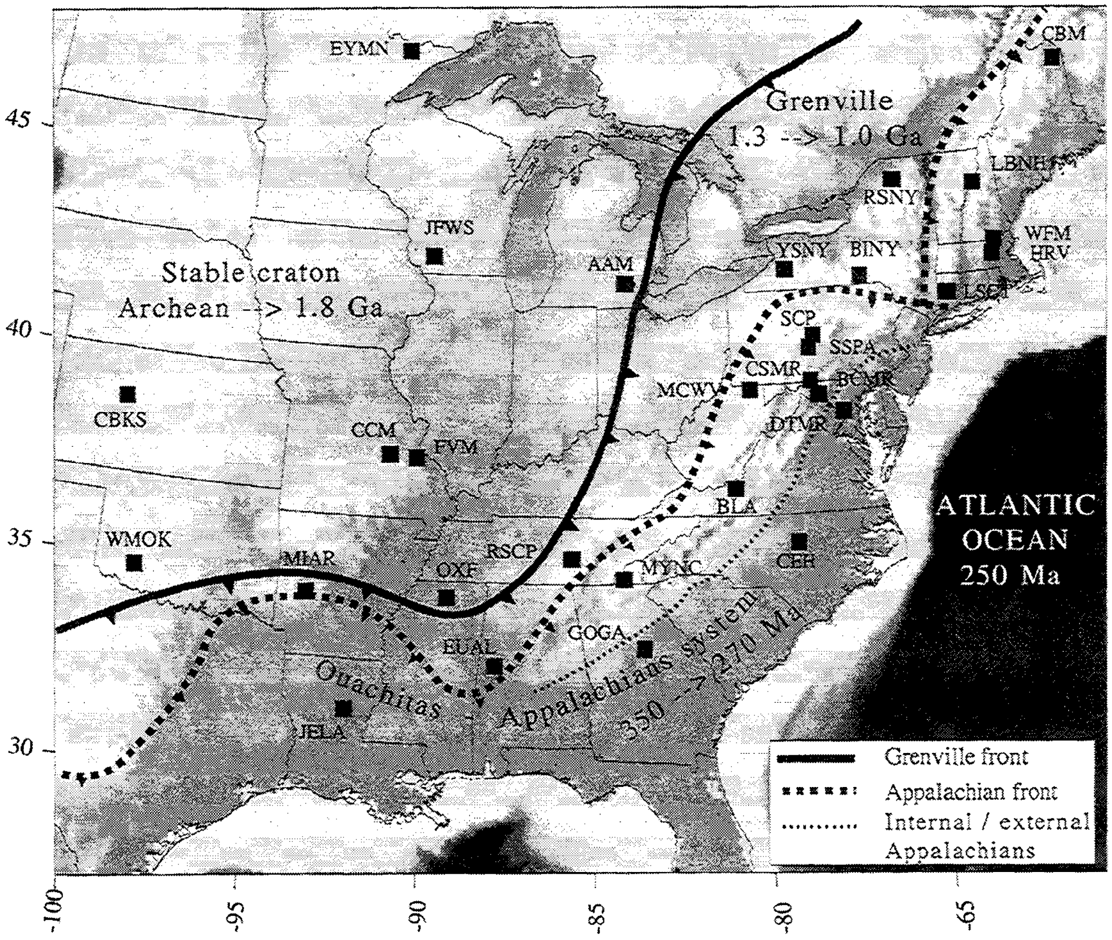


Figure 1. Topographic map of the eastern United States displaying station location and large-scale geologic features: Boundaries of the North American craton, of the Grenville belt, and of the external and internal Appalachians. An indicative time span for the building of these different lithospheric domains is also shown.

these assumptions are not strictly valid everywhere. The effect of a dipping structure in the mantle should create variation with a π periodicity of the parameters (ϕ,δt), and two layers of anisotropy should result in a $\pi/2$ variation of these parameters as a function of the backazimuth [*Silver and Savage*, 1994]. The apparent scattering that may be observed in the presented data set does not show clear evidence of such variations. An example of a good measurement at WMOK is shown in Figure 2. When the effect of the anisotropy (with the anisotropy parameters ϕ, δt) is removed, the energy on the initial transverse component disappears. The initial particle motion in the horizontal plane is typically elliptical and is linearized when the anisotropy is removed. Finally, the shape of the fast and slow split shear waves is remarkably similar, as expected when a shear wave is split in an anisotropic medium. Null measurements (absence of splitting) are also observed. An example of such data made at CEH is shown on Figure 3. In such a case, the energy is restricted to the radial component. It may be explained either by an absence of anisotropy or by the fact that the shear wave was initially polarized parallel to the fast or slow polarization direction in the anisotropic layer.

A basic assumption for teleseismic splitting measurements is that the shear wave is radially polarized at the core-mantle boundary. In most cases, an initial radial polarization seems to be a correct assumption and allows retrieval of well-constrained splitting parameters. In a few cases, however, this assumption appeared to be inappropriate and measurements were also performed without any assumption regarding the initial polarization direction of the shear wave. The algorithm developed by *Silver and Chan* [1991] searches for the values of splitting parameters (ϕ, δt) that minimize the smaller eigenvalue of the covariance matrix of corrected horizontal particle motion. It also estimates the corresponding initial polarization direction ϕ_0, which is generally close to the predicted radial direction. From a practical point of view, we systematically performed splitting measurements using the first assumption. When this first procedure gave poorly constrained results, we made a new attempt without assuming that ϕ_0 is in the radial direction. Results obtained by this second method were retained when they were clearly better constrained than for the first method. For this reason, we report in Table A2 the values of the event back azimuths, but we also report the estimated values of ϕ_0. In most cases, these two directions are very close (within a few degrees). In Table A2, a difference between the radial direction and the estimated ϕ_0 indicates that we kept the splitting parameters determined by minimizing the smaller eigenvalue. A typical plot of the computed initial polarization direction vs the backazimuth of the events is shown in Figure 4. For station WMOK, the initial polarization directions are close to the backazimuths, as expected, but it should be noted that variations of more than 10° are found in numerous cases. No consistent offset with backazimuth is present. Such differences between the backazimuth and the estimated ϕ_0 could be caused by lateral heterogeneity along the

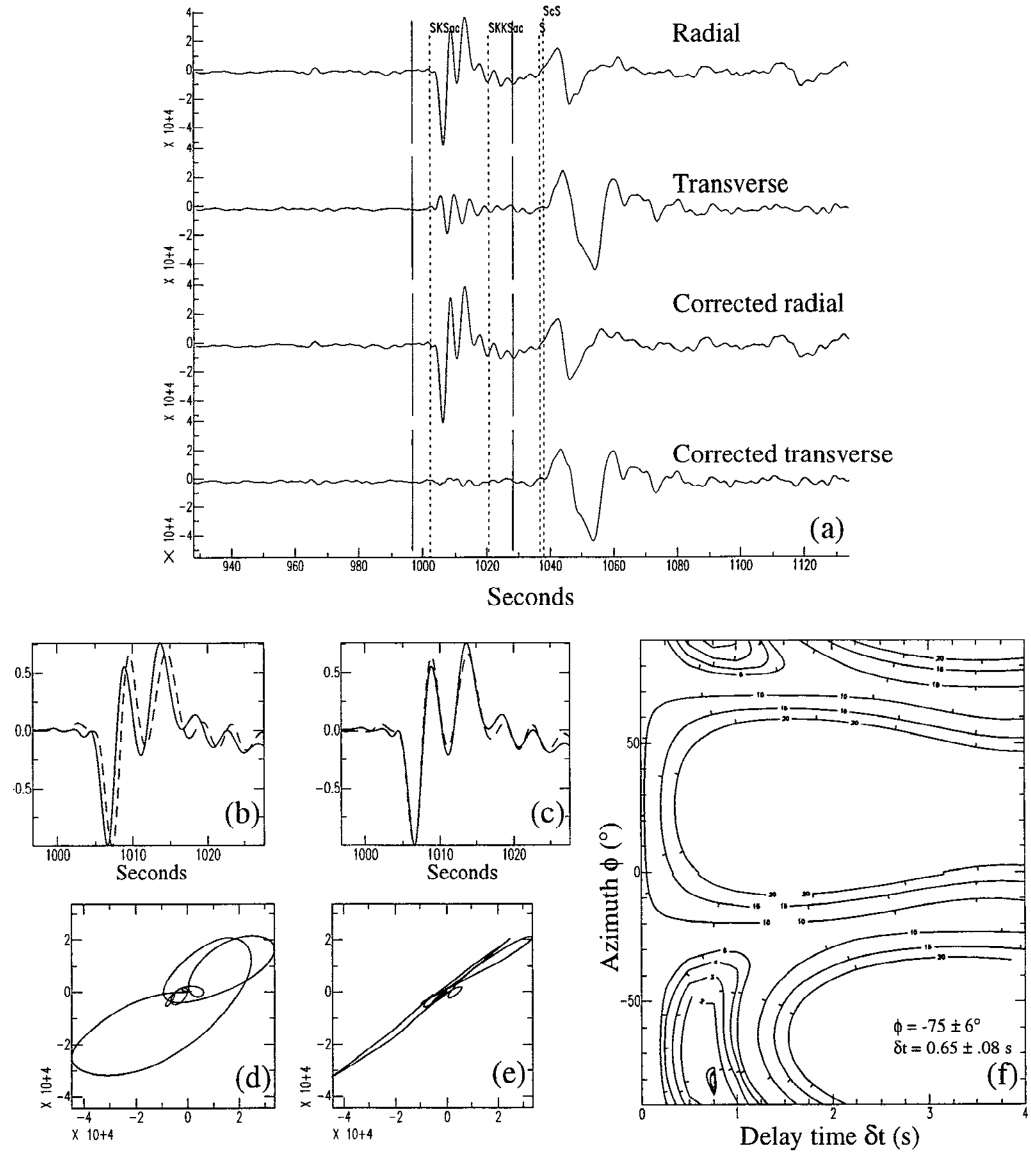


Figure 2. Example of splitting measurements: *SKS* phase for the event 94068 at WMOK. This event occured March 9, 1994, at 23:28:6.7 UT at a depth of 563 km, M_b=6.6, distance is 92° and backazimuth is N250°E. (a) Initial radial and transverse components with the anisotropy (note the energy on the transverse component) and with the anisotropy removed (no more energy on the transverse component). The vertical dashed lines represent the predicted phase arrival times from the IASPEI91 Earth model. The vertical continuous line represents the time window on which the splitting measurement is done. (bottom left) Overplot of the fast (solid) and slow (dashed) components of the split shear waves, (b) uncorrected and (c) corrected for the best calculated delay time. Particle motions in the horizontal plane are shown below, also (d) uncorrected and (e) corrected from the anisotropy. Note that the elliptical particle motion is well linearized when the anisotropy is corrected. (bottom right) (f) contour plot of energy on the transverse component as a function of the delay time δt (seconds) and the polarization angle ϕ (degrees) of the fast split shear wave. Double contours represent the 95% confidence interval. The fast polarization directions determined by this event for this stations (N75°W at WMOK) are clearly at a high angle from the absolute plate motion (APM) trending here N65°E. The same event at CBM also display a clear splitting but ϕ is oriented N34°E and δt is 1.05 s.

path. Apparent differences between the radial direction and ϕ_0 might also be related to instrumental misorientation, but this should result in a consistent pattern with the backazimuth. At MYNC, for example, such a pattern revealed that the east component had reversed polarity. The values of ϕ_0 were systematically symmetric around the N-S direction. For instance, a wave arriving at a backazimuth of 300° appeared to have an initial polarization direction of 60°. The results reported Table A2 for station MYNC are corrected from this problem.

Results

About 120 seismic events were processed following the method described above, allowing more than 600 splitting measurements (Table A2). We sorted the individual measurements into three groups, judged as good, fair, and poor, from four quality criteria: (1) The quality of the initial signal (signal/noise ratio and possible interference with direct S wave), (2) The ellipticity of particle motion in the horizontal plane when

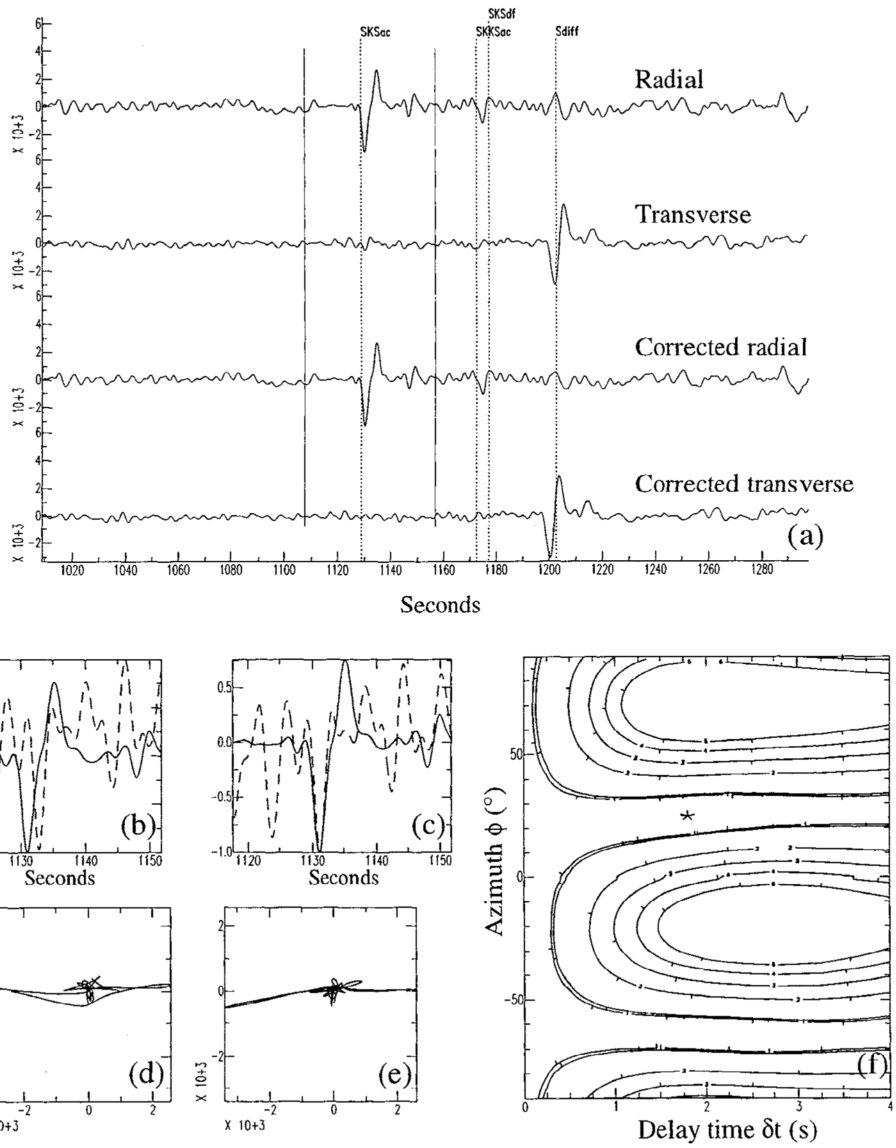


Figure 3. Typical example of a "null" measurement recorded at CEH for event 93284 (October 11, 1993) occuring at 15:54:21.2 UT at 351 km depth. M_b=6.4, epicentral distance is 104°, backazimuth is 328°. See Figure 2 for detailled signification of each diagram. (a) The *SKS* phase is well defined, but the energy is restricted to the radial component. No clear energy is visible on the transverse component. The *SKS* phase does not appear to be split. This kind of result may indicate either there is no anisotropy beneath the station or, more usually, that the initial polarization direction of the *SKS* wave was parallel to the fast or slow direction in the anisotropic layer. Null directions are expected to be consistent with non-null measurements. This consistency is clear for most stations (see BINY and LSCT, Figure 7 for instance). A single nonnull measurement was obtained at CEH but the numerous null measurements display a very good azimuth coverage (see Figure 7). This leads us to consider that there is no anisotropy (or at least only a weak anisotropy) beneath this station. In that case, a single event which gave a good splitting measurement remains unexplained.

anisotropy is present, (3) The linearization of particle motion by anisotropy removal, and (4) The quality of waveform coherence between the fast and slow split shear waves. A good measurement should have fulfilled the four criteria, a fair one three, and a poor one only two.

For most stations, we obtained reliable estimates of the two splitting parameters (Table A2). In Figure 5 the nonnull measurements obtained in this study are plotted for each station. In order to have the best control on the final results and also to discuss the various averaging methods, we determined the mean value characterizing the anisotropy at each station (see Table 1) by two different methods: (1) by weighting each individual measurement by its 1σ error reported in Table A2, method developed by *Silver and Chan* [1991]; and (2) by stacking individual splitting probabilities (see, for instance, Figure 2f). This method was developed by *C. Wolfe and P.G. Silver* (Seismic anisotropy of oceanic upper mantle: shear wave splitting methodologies and observations, submitted to *Journal of Geophysical Research*, 1996) in order to take into account the actual form of the probability distribution for (ϕ, δt). The null results were not taken into account, and we also discarded measurements for which the error in the delay time was larger

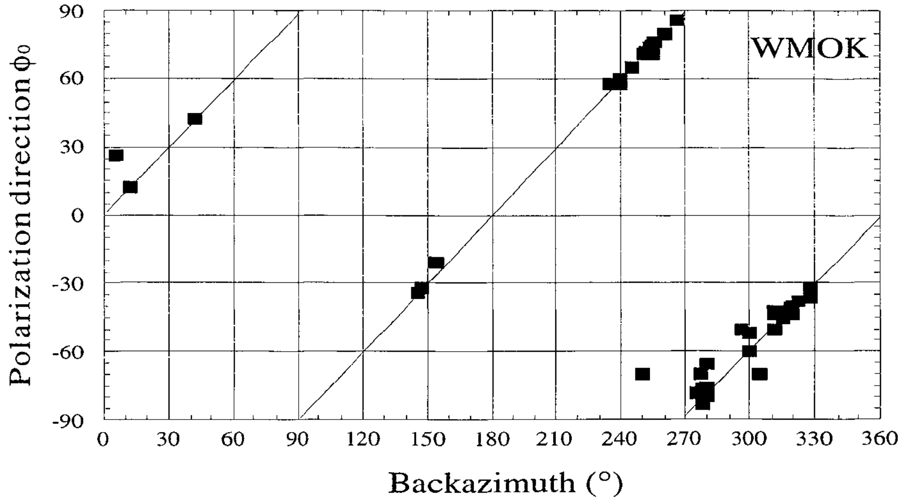


Figure 4. The "normal" way to perform a splitting measurement of core phases is to assume that the wave is initially polarized along the radial direction (the backazimuth) at the core-mantle boundary. In this case, the program minimize the energy of the transverse component in order to determine the best fitting ϕ-δt parameters. An alternative way is to perform a measurement without any assumption on the initial polarization of the wave. The program has to minimize the energy on the component corresponding to the smallest eigenvalue of the polarization matrix to get the splitting parameters [*Silver and Chan*, 1991], and it calculates the best polarization direction. In some cases, significantly better measurements were obtained using this second method. We plot here the polarization direction determined by the program as a function of the backazimuth (the theoretical polarization direction). At station WMOK, for instance, theoretical and actual polarization directions are close from each other but one can note that differences more than 15° may be found for some events.

than the delay time itself. The results obtained by the two methods are clearly in good agreement (see Table 1). The discrepancy is usually within the error bars, and the largest values are found for stations for which we have only a few constrained results.

The number of individual splitting measurements taken into account in the calculation of the mean splitting parameters is clearly an important factor. We report (Figure 6) the 1σ error in ϕ and δt calculated by the weighting averaging technique as a function of the number of individual measurements taken into account in the calculation. As expected, an increasing number of measurements leads to better constrained final results. Mean splitting parameters derived from more than five individual measurements are generally well constrained (error of less than 6° in ϕ 0.15 s in δt). The less constrained results are derived from fewer than five individual measurements. For this reason, the final mean splitting results shown in Table 1 and plotted Figure 8 are sorted in two classes: the best constrained parameters deriving from at least 5 individual non-null measurements (in black), and the less constrained results obtained from less than five non null measurements (in gray).

Most seismic events (Table A2) yielded null results similar to the one presented in Figure 3. For the ϕ direction given in Table A2, we kept the estimated value, which may differ by 5° from the polarization direction in certain cases. For a given station, however, null and nonnull measurements are expected to give consistent results. Some examples are shown in Figure 7: the two stations LSCT and BINY give consistent null and nonnull results; the calculated mean fast polarization direction is oriented roughly E-W (N83°E and N101°E respectively) and is consistent with the roughly E-W and N-S trend of backazimuths for which no splitting has been detected. On the other hand, the two stations DTMR and CEH display much more complex patterns. At DTMR, well-constrained nulls cover a large range of possible backazimuths and together with the single, poorly constrained result, seem to indicate weak anisotropy beneath this station. At CEH, numerous good nulls were obtained over a very good azimuthal coverage. Such a pattern points to an apparent absence of anisotropy that will be discussed later. The two nonnull "good" measurements are therefore difficult to understand in such a context. Given the large number of null results, we have classified this station as having splitting below the detection limit.

From the statistical analysis of our data set, it appears that at several stations, anisotropy was not detected by the incoming shear wave when its initial polarization was at an angle up to 20° from the fast or slow direction of anisotropy. For the station LSCT or BINY, for instance, Figure 7 shows that waves arriving at backazimuth close to 340° gave null results, whereas the actual anisotropy is characterized by fast split shear wave oriented roughly E-W. This implies that from the whole range of possible backazimuths (360°), merely half of them may detect the anisotropy. Two major effects may explain this large number of null measurements. The 1 sample/s long-period data from the USNSN may not be sensitive enough to detect weak splitting. The second effect that may explain the small number of nonnull measurements is that most recorded events originate in subduction zones of the western Pacific and reach the eastern United States with backazimuths in the range 300-340, i.e., close from a null direction for the stations for which ϕ is oriented around N60°E.

Some discrepancies may be found between our findings and preexisting studies. *Levin et al.* [1996] recently determined splitting parameters for three of the same stations: BINY, LSCT, and HRV. The results at BINY agree fairly well, but the results at the two other stations clearly differ. At LSCT, for event 950326, for instance, they found parameters (ϕ, δt) of 165° and 1.0 s,

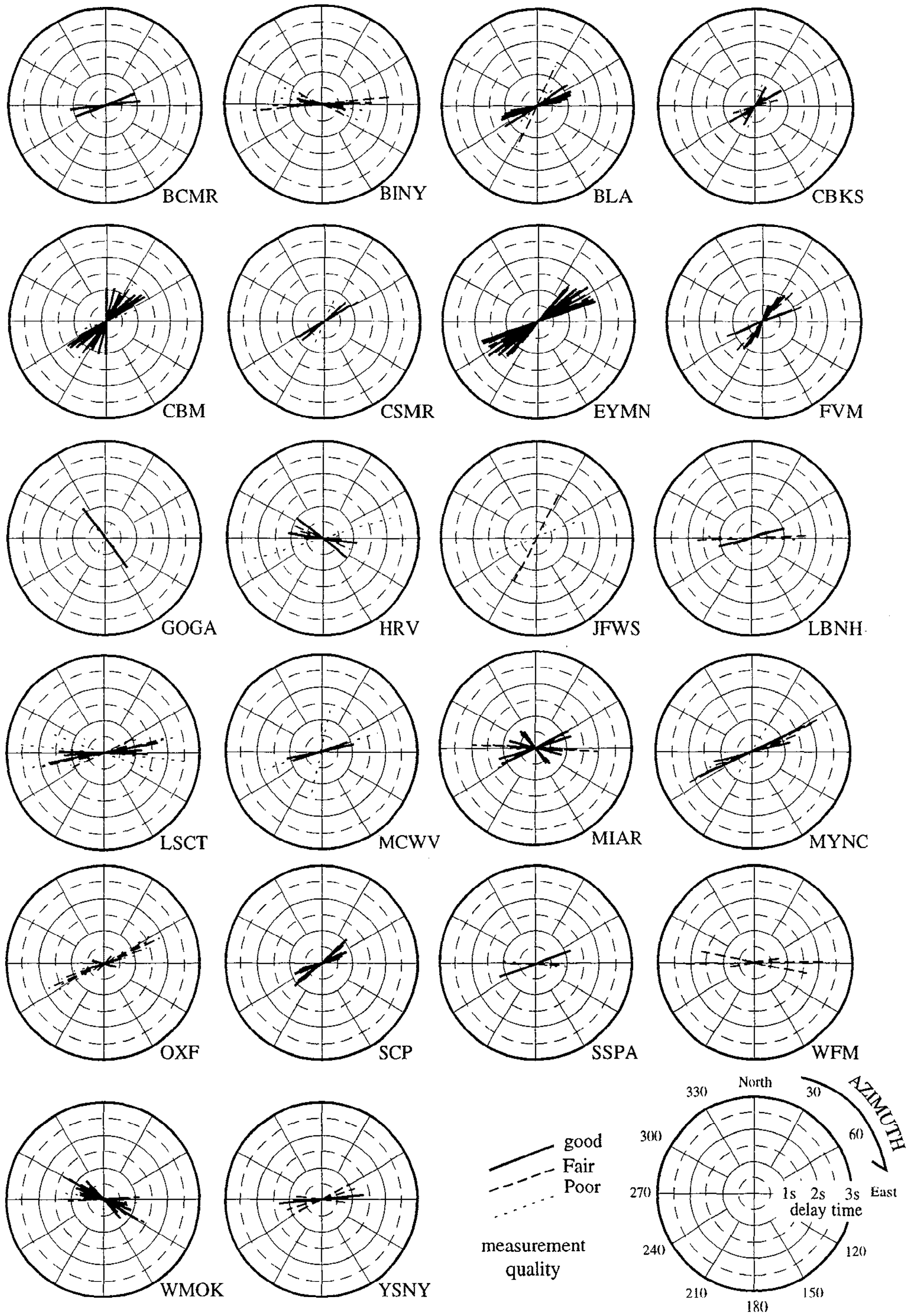


Figure 5. Summary of nonnull measurements. For each station, the orientation of the segment represent the azimuth of the fast split shear wave and its length is proportional to the delay time (up to 3.0 s). The signification of the measurement quality is in the lower right corner. Solid lines correspond to well constrained results, large dashed lines correspond to fair results and small dashed lines correspond to poorly constrained results. It is important to note that this representation only plot the best parameters found by the program in the 95% confidence area and do not take into account the shape of this confidence interval (see Figures 2f and 3f) which can be sometimes of rather complex geometry. Some apparent scattering and inconsistency in the results (at MIAR for instance) are, in fact, fully consistent considering this confidence interval.

respectively, whereas we found 80° and 2.0 s. However, we graded this measurement as poor on the basis of relatively high level of noise in the data and in the poor coherence between the fast and slow split waves. At this station, we used 28 individual events which resulted in 13 nonnull individual measurements and 20 null directions compatible with the nonnull directions (see Figure 7), whereas *Levin et al.* [1996] made only four individual measurements at this station. At HRV, the 23 events used gave six nonnull splitting measurements. We considered as null measurements the four nonnull measurements that *Levin et al.*

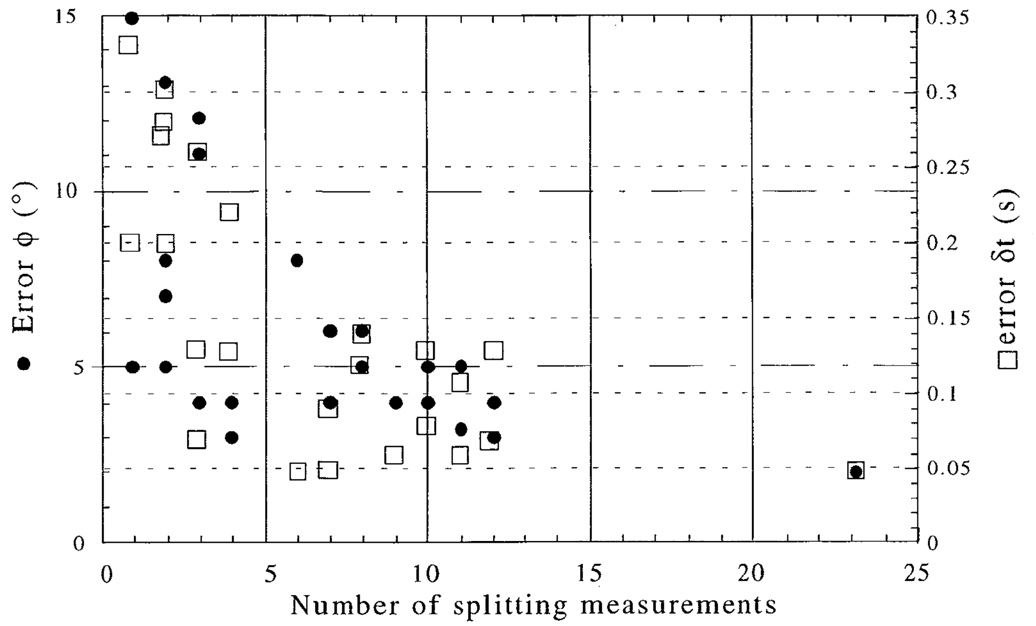


Figure 6. Average ϕ and δt error (represented by the solid circles and the open squares respectively) as a function of the number of measurements taken into account in the calculations of the mean parameters. A large number of measurements is important to get well constrained average values (reported in Table 1). Although well-constrained results may be obtained in certain cases with less than five individual measurements, it appears clearly that the larger the number of splitting measurements, the smaller is the error and the better constrained is the calculated average. The less constrained results are systematically obtained with less than four splitting measurements. Alternatively, above seven measurements, error is systematically smaller than 6° on ϕ and 0.15 s on δt. This diagram clearly shows that one has to be aware in interpreting data resulting from only few events, what is generally the case in portable experiment.

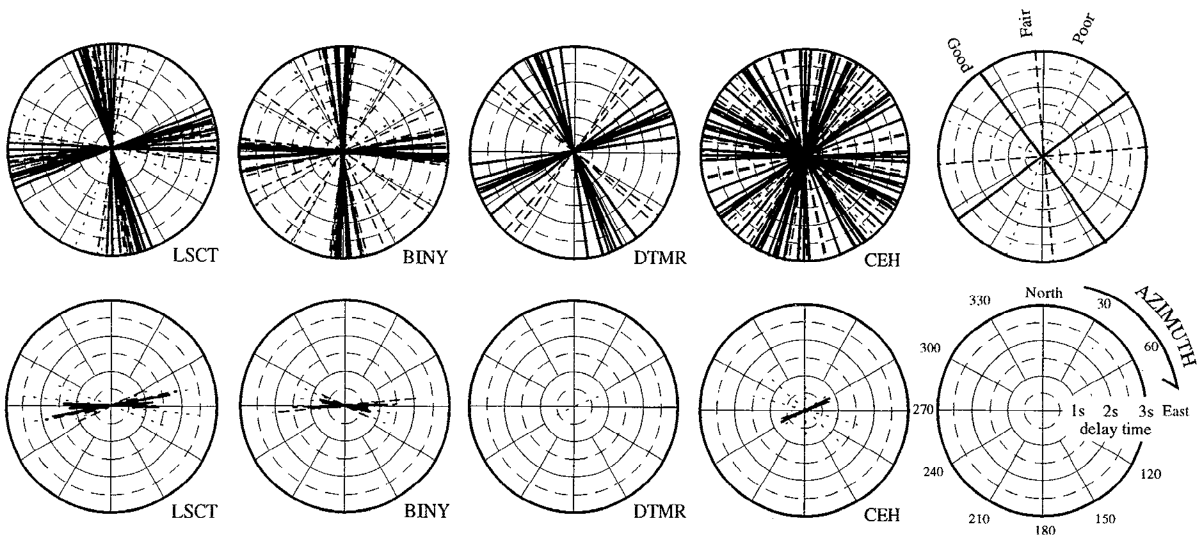


Figure 7. Typical examples of nonnull versus null measurements at four stations. As explained in the text, null and nonnull measurements should be consistent. The null directions correspond to backazimuth from which no splitting has been detected (compare Figure 3). Consistent results are obtained at BINY and LSCT. The roughly E-W trend of the fast split shear wave is coherent with the N-S and E-W trend of nulls. It should be noted, however, that nulls have been obtained at relatively large angle from the actual E-W fast polarization direction. CEH and DTMR display much complex patterns that could be interpreted in terms of absence of anisotropy. A single nonnull measurement has been obtained at DTMR, but it is poorly (as defined in the text) constrained, and good nulls have been found. At CEH, numerous clear null measurements were obtained with a very good backazimutal coverage, and only two nonnull splitting measurements were obtained. This station displays a clear, and still unexplained, inconsistency between nulls and nonnulls measurements.

made on the *SKS* phase. For these specific records, an absence of splitting is supported by the weakness of the energy on the transverse component that was at the level of the background noise. It should be noted that we graded their events as fair or poor as defined above. Furthermore, we generally avoided filtering the data, except in cases where long-period (above 50 s) and high-frequency (above 5 Hz) noise had to be removed. We did perform a series of tests on our data, using filtering similar to that used by *Levin et al.* [1996]. Even in this case, however, we did not obtain comparable results. We would regard our results as better constrained, based on our expanded data set. Comparing our results at SCP and WFM with those of *Vinnik et al.* [1989; 1992] reveals relatively small differences that are within the estimated uncertainties. Our mean result at WFM (N96°E and 1.1 s) is also in agreement with the single nonnull *SKS* measurement (N97°E and 0.8 s) made by *Ansel and Nataf* [1989].

Origin of the Anisotropy: Lithospheric or Asthenospheric?

A key issue in the study of mantle anisotropy is determining the physical process responsible for the corresponding upper mantle deformation. As a first step, we will examine those features in our data set may be diagnostic of a dominant asthenospheric or lithospheric origin.

Angular Relationships of ϕ to the North American Absolute Plate Motion and Asthenosphere Flow-Related Anisotropic Models

The most straightforward asthenospheric flow model for predicting the pattern of splitting parameters is 'simple asthenospheric flow'. In this case the asthenosphere is assumed to be in the form of a mechanical decoupling zone between the plate and the moving mantle below. Progressive simple shear is developed in the asthenosphere, and for a vertical propagation direction, ϕ is predicted to be parallel to the absolute plate motion (APM) direction. A histogram of the difference between ϕ and the value predicted by this model indeed shows a peak around a value of 0 [*Vinnik et al.*, 1992] suggesting a correlation. However, as noted in the introduction, there is an important ambiguity in interpreting splitting data in stable North America, in that the large-scale geologic features of the region are roughly parallel to the APM direction. In order to resolve this ambiguity it is necessary to examine a denser distribution of stations. Indeed, the present data reveal a more complex anisotropic pattern. The present-day motion of North America relative to hotspots incorporating the NUVEL-1 model [*Gordon*, 1995; *Gripp and Gordon*, 1990] is ~28 mm/yr toward WSW (about W25°S; see Figure 8). Several stations located in the Appalachians display ϕ directions parallel to APM. However, a more detailed examination of individual results reveals a noticeable obliquity between the observed fast split shear waves and the APM in many places. This angular difference is large enough to be statistically significant: 25° at CBM, 25 to 35° for stations BINY, LSCT, WFM, and HRV that display homogeneous results at the regional scale, 20° at MIAR in the Ouachitas, 45° at WMOK in the Wichita Mountain, and 30° at CCM and FVM. These numbers are about 5 times larger than the 1σ errors. The very clear splitting observed at stations WMOK and CBM for the event 94068 (Figure 2) is particularly demonstrative: the fast split shear wave is oriented N115°E and N34°E, respectively. Both results are far from the APM-predicted fast split shear wave.

If the anisotropy is primarily generated by asthenospheric deformation in response to the present-day motion of the plate, and assuming an asthenosphere of constant thickness and anisotropy, then homogeneous fast polarization directions (around N65°E), and delay times should be observed. This is clearly not the case in many places; we conclude that simple asthenospheric flow does not provide an adequate, overall explanation for the data set.

More complex asthenospheric flow models have been introduced in the last few years to account for short-length-scale variations in orientation and magnitude of shear wave splitting, under the assumption that the asthenospheric contribution is dominant. For example, *Makeyeva et al.* [1992] interpreted splitting variations observed in the Tien Shan in terms of small-scale convection in the upper mantle beneath the belt. While perhaps plausible for the Tien Shan, this interpretation may be less appropriate for the eastern United States, where there has been virtually no tectonic activity for at least the last 100 Myr.

Others have proposed alternatives to simple asthenospheric flow in which the flow is deflected around the thick cores of continents. For example, *Bormann et al.* [1996] suggested that variations in ϕ in central Europe are due to channeling of asthenospheric flow around regions having a thicker lithosphere. This hypothesis is appealing and splitting observations should be compared to data on the lithosphere thickness beneath the eastern United States. Variations in upper mantle shear velocities observed by *Grand* [1994] beneath the North American plate were interpreted in terms of a cold cratonic root. An increase in lithospheric thickness toward the center of the continent is expected from these observations. On the other hand, the data provided by *Grand* [1994] do not suggest any significant thickness variation in the eastern part of the North American plate (the Appalachian and Grenvillian domains). Shear wave tomography performed by *Van der Lee* [1995] compares reasonably well with the previous model: The Appalachian and Grenvillian domains appear as "normal" lithosphere (about 100 km thick), wrapping around the thick (more than 200 km) North American craton. Beneath a thick and cold lithosphere, the development of an asthenosphere may be suppressed, and the anisotropy could be primarily of lithospheric origin. Alternatively, beneath a thinner lithosphere, it may be possible to develop an asthenospheric decoupling zone [e.g., *Tommasi et al.*, 1996], in which case the anisotropy may record a significant component related to deflected flow around lithospheric roots. At the plate scale, the rotation of ϕ from E-W in the south to NE-SW in the eastern part of the continent could be compatible with a model of asthenospheric flow deflected around the North American craton. However, while this model may explain reasonably well the large-scale trend of ϕ, it cannot explain small-scale variations in splitting parameters observed within the Appalachian, Grenvillian, and cratonic domains.

Small-length-scale variations of the splitting parameters

In several places, small-length-scale variations of both the splitting parameters ϕ and δt have been observed. For instance, the following:

1. In the northeastern United States, the stations YSNY, BINY, LSCT, WFM, and HRV are characterized by a roughly E-W orientation of the fast split shear waves. This clearly contrasts with results obtained in the northern Appalachians at CBM (ϕ = N39°E) and DRLN (ϕ = N29°E), a station from the Canadian National Seismic Network (M. Bostock and J. Cassidy,

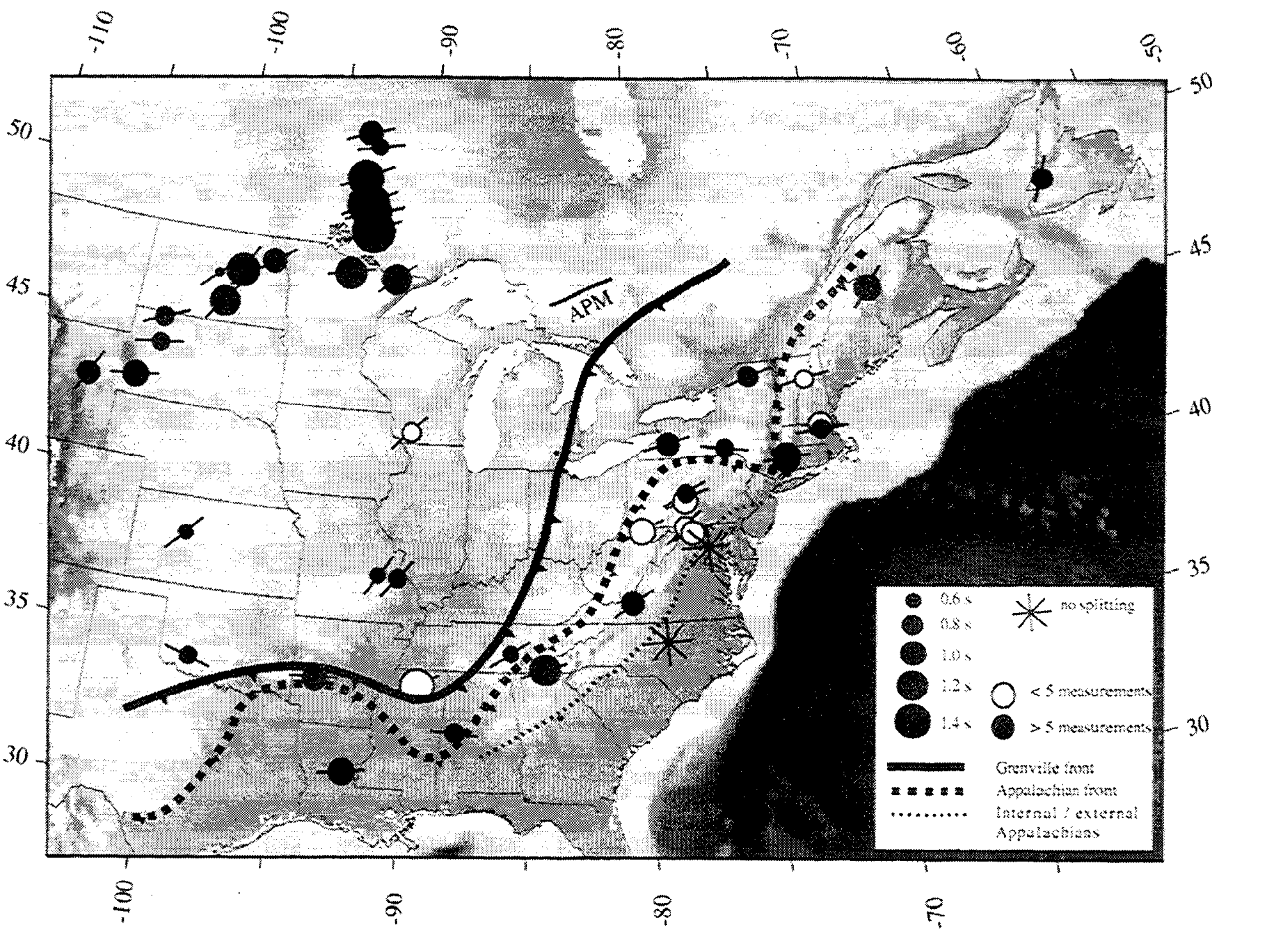


Figure 8. Map of the average splitting results calculated from individual measurements by weighting each individual measurement by its 95% confidence interval. Well constrained results (more than five individual splitting measurements) are displayed in black, and less constrained results (less than five individual nonnull measurements) are presented in grey. The size of the circle is proportionnal to the delay time, as indicated in the legend. The large-scale geologic boundaries are shown. Results at GOGA is not shown because deriving from a single non-null measurement (*SKKS* splitting, event 94068) which is not consistent with the absence of splitting found for the same event for the *SKS* phase. Are also shown on this map two results kindly communicated by E. Sandvol and J. Ni (personal communication, 1996) for the LRSM stations JELA and EVLA, results from M. Bostock and J. Cassidy (unpublished results, 1996) at DRLN and the results from *Silver and Kaneshima* [1993] for the North American craton.

unpublished data, 1996), and in the central Appalachians at SCP and SSP (ϕ = N65°E).

2. In the central Appalachians, two stations display contrasting well-constrained results: BLA (ϕ= N58°E, δt= 1.1 s) and CEH (absence of anisotropy). A similar contrast is found farther north in a similar geological environment between the stations BCMR (ϕ= N73°E, δt= 1.0 s) and DTMR (no anisotropy detected). Variation over this short distance is consistent with the dimension of the Fresnel zones for the seismic waves used. At the 90 km spacing between BCMR and DTMR, these two stations are predicted to possess nonoverlapping Fresnel zones for anisotropy residing in the top 200 km of the mantle (see *Alsina and Snieder* [1995] for a discussion).

3. In the Oklahoma-Arkansas-Missouri area, the two stations CCM and FVM are characterized by a fast split shear wave oriented N35°E and N42°E, respectively, and contrast with the results at WMOK in the Wichita mountains (ϕ = N109°E) or MIAR in the Ouachitas (ϕ = N89°E).

4. In the southern Appalachians, nearby stations characterized by similar ϕ display relatively large variations in δt (e.g., at RSCP δt = 0.75 s and at MYNC δt = 1.38 s).

These small-scale variations are not compatible with a deep source of anisotropy but rather suggest a significant participation of the lithosphere structure in the observed shear wave splitting.

Correlations of δt With the Lithosphere Thickness

Positive correlation of the observed delay times with lithospheric thickness may also support the hypothesis of a lithospheric origin of anisotropy. Assuming a roughly homogeneous intrinsic anisotropy in the lithospheric mantle, larger values of δt may be expected above thicker lithosphere. For the North American craton, a correlation between δt and (predicted and observed) S wave travel time delays at the different stations, was already described by *Silver and Chan* [1991], *Silver and Kaneshima* [1993], and *Silver* [1996], who noticed that the largest delay times were found where the earliest arrivals of *S* waves were recorded. Early arrivals were interpreted as due to a thicker lithosphere root. Our data set displays a similar trend. CCM and FVM, which are located on the southern edge of the craton where *S* velocity anomalies support a lithosphere about 100 km thick [*Grand*, 1994], display small delay times (0.73 and 0.83 s, respectively). On the other hand, EYMN which is located inside the craton above much deeper-rooted *S* velocity anomalies (down to 300 km) displays larger δt (1.38 s). Despite the few observations available across the North American craton and its surrounding terranes, our results are consistent with a thickening of the lithosphere toward the center of the craton. In addition, combined seismic and magnetotelluric anisotropy studies across the Grenville front in Canada [*Sénéchal et al.*, 1996] clearly favor a lithospheric origin for the anisotropy. By contrast, an asthenospheric model does not easily account for the largest delay times being associated with the center of the craton.

There is one particular area where that does not fit into this simple picture of lithospheric deformation, namely an east-west band of stations extending from western New York to the east coast. This domain is characterized by a relatively thin lithosphere (see discussion below), based on tomography [*Van der Lee*, 1995] and observed delay times of up to 1.4s (LSCT). This either requires somewhat higher intrinsic anisotropy than the range 3-5% usually assumed, or the existence of a significant asthenospheric contribution.

Absence of Detectable Splitting at Two Stations

The absence of detectable anisotropy at DTMR and CEH also argues in favor of a lithospheric source of anisotropy. Such absence of anisotropy is not compatible with a model of simple asthenospheric flow. At CEH (North Carolina), for instance, although 3 years of data were processed, no clear evidence of anisotropy was found. Figure 7 displays the plot of all null measurements obtained at this station. The very good coverage in backazimuth led us to the conclusion that the absence of splitting is well constrained.

An absence of splitting may result from the presence of two anisotropic layers displaying orthogonal directions of fast shear wave and similar δt. In such a case, it is not possible to constrain the nature of the layers (lithospheric mantle, asthenosphere) and the tectonic processes that may generate these two anisotropic layers, although it would suggest the contribution of both a lithospheric and asthenospheric contribution. Assuming a single anisotropic layer in the lithosphere, three possible explanations may account for these observations:

1. The deformation of the lithospheric mantle (and therefore its intrinsic anisotropy) is homogeneous over the eastern Appalachians, but the lithosphere is too thin (< 50 km) to generate a detectable signal. CEH and DTMR are the closest stations to the continental margin and lie on the boundary of Permian basins; the lithosphere beneath these stations may have been thinned or perturbed during the Atlantic rifting, and its internal pervasive structures may have been partially or totally erased .

2. The lithospheric thickness is homogeneous over the eastern Appalachians, but the intrinsic anisotropy of the mantle beneath these stations is too weak (< 2%) to generate a delay time large enough to be above the detection limit (~0.5 s). The upper mantle fabric may have been erased by annealing due to a thermal event, related, for instance, to the Atlantic rifting.

3. The mantle flow beneath these stations is characterized by a fossil vertical olivine lineation. Seismic properties of upper mantle nodules [*Ji et al.*, 1994; *Mainprice and Silver*, 1993] are systematically characterized by the smallest shear wave birefringence for propagation directions close to the rock lineation. It remains difficult, however, to rationalize a process that may have produced vertical mantle flow in this area.

4. Finally, the structure of the lithosphere could be sufficiently complex in the orientation of anisotropic structures so as to be effectively isotropic in a path-average sense. This might occur, for example, as a result of superimposed processes, such as the Appalachian collision and subsequent Atlantic Ocean opening.

In summary, in terms of asthenospheric models for anisotropy, the data are not compatible with simple asthenospheric flow. The values of ϕ that are closest to the APM direction are within the cratonic core where the origin appears to be in the lithosphere, based on the distribution of delay times. The splitting observed along the southern and eastern margins of stable North America may be compatible with asthenosphere flow deflected around the continental root of North America. However, a significant to dominant participation of the lithospheric structure is probably necessary in several places to explain small-scale variations in the splitting parameters.

Correlation of Seismic Anisotropy With Geological Structures

Because anisotropy is related to both olivine's intrinsic seismic properties and preferred orientation in the upper mantle, measurements of shear wave splitting may provide insight into the tectonic fabric of the lithosphere. Any attempt to relate shear wave splitting to geological structures and past tectonic processes in the eastern United States should take into account that the eastern North American continent results from a complex history involving successive terrane accretions, orogenies, and continent breakup. Three main continental domains may be defined: the Archean (> 2.5 Ga) to early Proterozoic (2.5 - 1.6 Ga) cratonic core of the continent, the Grenvillian domain built 1.3 to 1.0 Ga, and the Appalachians/Ouachitas domain resulting from several collisions during the Middle Ordovician to Permian. In terms of candidate tectonic processes, not only do orogenies have to be considered but continental rifting/breakup as well. This latter process was twice active in eastern North America: first at around 600 Ma, when western Gondwana began to breakup and the Iapetus Ocean formed between North and South America, and next around 250 Ma during the initial rifting of the North Atlantic ocean and the breakup of Pangea.

Anisotropy in the Cratonic Nucleus

In this study, splitting parameters have been retrieved for only a few stations located on the craton compared with the numerous stations in the Appalachians. Together with our results, we report (Figure 8) the observations made farther west on the Canadian shield by *Silver and Kaneshima* [1993]. The amplitude of δt at EYMN (1.38 s) is in good agreement with their neighboring results that display also rather strong δt (e.g., MAMW, 1.30 s, DLOR ,1.75 s, or CROW, 1.60 s). The orientation of ϕ at EYMN (N52°E) compares fairly well with measurements at neighboring stations such as DLOR (N66°E), EFOR (N64°E), or FVNR (N54°E). It differs significantly from ϕ at MAMW (N81°E); the splitting at this station, however, is estimated from a single measurement.

Although the stations for which we retrieved splitting parameters lie in domains of different age, the fast split shear waves display a roughly homogeneous NE-SW direction. Most of the craton in the study area is covered by sedimentary rocks, and little is known about its tectonic fabric; this makes it difficult to compare anisotropy data with surface geology in an attempt to derive an interpretation in terms of deep lithospheric structures. In some cases, the basement is exposed. For example, at EYMN, the fast split shear wave polarization is parallel to the tectonic fabric of both the Superior province [*Silver and Kaneshima*, 1993] and the midcontinental rift. As previously discussed, a good correlation is observed between the measured delay time and the thickness of the lithosphere beneath the craton as deduced from S wave tomography.

Anisotropy in the Grenvillian Domain

The Grenville belt formed from a collision between the North American and the Amazon cratons 1.3-1.0 Ga. It is a major orogen extending over more than 3000 km in length and 500 km in width. This belt is well known in the Canadian shield where tectonic, petrological, and geochemical evidence indicates that the entire lithosphere was deeply involved in orogenic processes [e.g., *Hoffman*, 1989]. Southward, exposures are scarce, but magnetic and gravimetric anomaly patterns characteristic of the different domains of the belt defined in the northern area allowed identification of buried terranes and extrapolation of their limits [*Hinze and Hood*, 1989]. The Grenville belt displays a curvature of its structural trend from NE-SW (and in some areas N-S) in the eastern United States to almost E-W in the southern United States and therefore wraps around the North American cratonic nucleus. The eastern limit of the Grenvillian domain is more difficult to delineate. After the Late Proterozoic opening of the Iapetus ocean, this boundary corresponded to the eastern margin of the North American continent and displayed several promontories and reentrants [*Thomas*, 1977]. Surface geology shows that the Grenville belt is currently bounded eastward by the front of the Appalachian orogen. COCORP seismic profiles (Figure 9), however, indicate that the Grenvillian domain extends eastward beneath the Appalachians up to the Inner Piedmont [*Cook et al.*, 1979; *Hatcher and Zietz*, 1980; *Cook et al.*, 1981]. Extensional structures related to the Late Proterozoic rifting are still preserved and this suggests that the Grenville basement beneath the western Appalachians escaped from significant reworking during the Paleozoic orogenies. It is reasonable to conclude that in domains where the middle and lower crust escaped farther pervasive deformation, the upper mantle also retained a Grenvillian fabric. Assuming a lithospheric origin of the anisotropy, stations located in the western (external) Appalachians (Figures 1 and 8) most likely record an anisotropy related to the Grenville orogeny and not to the Appalachian one (Figure 9). For this reason, results obtained at stations located in the western Appalachians (Blue Ridge and Valley and Ridge) are considered belonging to the Grenvillian group and not to the Appalachian one. The most spectacular result for the Grenvillian domain is the conspicuous correlation of the orientation of the fast split shear waves with the structural trend of the belt. The ϕ direction progressively rotates from E-W at MIAR in the southwestern part of the belt, to N60°E at MCWV and SCP in the central part of the belt, and follows closely the curvature of the Grenville belt. The amplitude of the observed delay times and the correlation of ϕ with the structural grain of the belt are consistent with the observations made farther north in Canada by *Sénéchal et al.* [1996] on the Grenville Front.

The parallelism between the anisotropy, the structure of the belt, and the boundary of the craton, if indeed this indicates a causal relationship, has important consequences for continental assembly. For example, *Vauchez and Barruol* [1996] discuss the influence of tectonic inheritance on subsequent tectonic events, especially the control of a mechanical anisotropy inherited from the Grenville event on the initial geometry of the breakup of the continents.

Anisotropy of the Appalachian Domain

The Appalachian orogen involves several domains that have undergone contrasting evolutions. Anisotropic parameters, therefore, should be discussed taking into account the progressive formation of the belt during the Paleozoic. The Appalachians are divided into the northern and central southern units; the boundary between both domains is broadly marked by the E-W oriented Martic line in the New York area. The Paleozoic orogenic evolution of the northern domain ended in the Carboniferous when the European continent (involving part of North Africa) collided with North America, resulting in the building of the

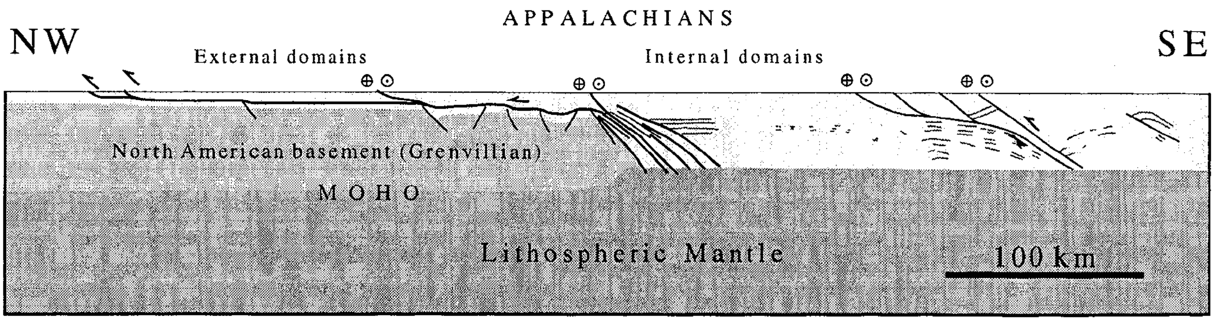


Figure 9. Interpretative geological cross-sections of the crustal structures of the southern Appalachians from the COCORP seismic profile, modified from *Cook et al.*, [1981] with the permission of the publisher, the Geological Society of America. This profile clearly shows that the external Appalachians are characterized by a thin-skinned tectonic in the upper crust above an undeformed Grenvillian basement. Therefore, if one assumes the anisotropy is primarily located in the lithospheric mantle, seismic stations located on the external Appalachian units record a "Grenvillian" anisotropy.

European Hercynian belt. The central and southern Appalachians have formed during a long period of convergence with the African continent that was separated from the Eurasian continent by a continental-scale transcurrent fault that accommodated relative motions of both continents [e.g., *Lefort and Van der Voo*, 1981]. The convergence between North America and Africa was oblique and this induced a transpressional regime that favored the development of continental, orogen-parallel strike-slip faults [*Vauchez et al.*, 1987]. Lateral escape was even enhanced in the late stages of the collision when the Reguibat promontory of West Africa impinged the North American margin in the Baltimore area, provoking a large curvature of the Appalachian structural trend in this area and a southwestward extrusion of the internal domain of the southern Appalachians [e.g., *Vauchez et al.*, 1993]. Thrust and nappe tectonics is largely dominant in the northern Appalachians, with only a subsidiary contribution of orogen-parallel motions. In the southern Appalachians, orogen-transverse thin-skinned tectonics dominate in the external Valley and Ridges Province, thick-skinned tectonics in the central Blue Ridge Province, and orogen-parallel transcurrent motions in the internal Piedmont Province. From seismic profiles performed in the Southern Appalachians [e.g., *Cook et al.*, 1979, 1981], it was suggested that the North American lithosphere extends far eastward beneath the belt and that a transition to an accreted lithosphere only occurs beneath the western Piedmont (Figure 9). This situation is the result of the late stages of the collision when crustal formations have been transported northwestward on top of the cratonic lithosphere. As stated previously, for this reason we will consider that stations characteristic of the Appalachian domain are only those located in the internal part of the belt (Piedmont domain).

The pattern of splitting parameters is more complex in the eastern (internal) Appalachians than in the Grenvillian domain. A very clear parallelism of ϕ with the northern Appalachians structural grain exists at CBM, and was also observed by *M. Bostock and J. Cassidy* (unpublished data, 1996) at DRLN. As discussed above, for these stations, ϕ is at a high angle from the APM (at 26° and 36°, respectively). This points to a coherent deformation of the crust and the lithospheric mantle in this zone. On the other hand, CEH and DTMR in the central southern Appalachians are both characterized by an absence of detectable splitting. These two stations sit on the internal domain of the belt, which would be expected to be the most deformed zone. In this domain, lateral escape of lithospheric blocks was accommodated by orogen-parallel transcurrent-faulting [*Vauchez et al.*, 1993] and may have generated a pervasive deformation in the lithospheric mantle. A fast split shear wave parallel to the strike of the belt [*Vauchez and Nicolas*, 1991] and large delay times would be predicted.

The subsequent rifting of North America may have played a role in weakening the fabric imparted by the Appalachian orogeny. Continent breakup began shortly after the end of the orogen, and its effects may be observed far inside the plate. Kimberlite-type magmatism seems to be the earlier effect and has been interpreted in terms of asthenospheric upwelling [*Taylor*, 1984]. These intrusions are found all along the east coast and span in age from late Carboniferous in the south to Jurassic-Cretaceous in the north. There are also numerous exposed or inferred rift basins, Permian in age, that closely follow the Appalachian structural trend [*Sheridan*, 1989]. Since the oldest true oceanic lithosphere is 160 Ma, these geologic evidences emphasize that ocean opening has been a long term process. Finally, there is vast system of doleritic dykes up and down the east coast of the United States that has been termed the Eastern North America Dolerite Province [*McHone and Butler*, 1984], whose eastern boundary is shown in Plate 1a. We note that this boundary separates the two stations CEH and DTMR where anisotropy is weak, from those farther to the west with observable splitting, suggesting the rifting was, in fact, the cause. This relationship suggests that the rift-related magmatism weakened the effective anisotropy. Similarly reduced anisotropy is also a basic property of the mantle wedge above convergent margins, where deformed regions (such as Japan and the Andes) have been subject to igneous activity [*Silver*, 1996].

The E-W ϕ Anomaly

The transition between the northern and the central southern Appalachians is sampled by five stations characterized by homogeneous ϕ directions, trending roughly E-W (see Figure 8 and Plate 1a). This regional trend strongly contrasts with measurements farther south (ϕ around N65°E) and with those farther north at CBM (ϕ = N39°E) and DLRN (ϕ=N29°E) and therefore defines an anomalous domain in the general pattern. A striking feature of this anomaly is that the orientation of the fast split shear waves clearly display strong obliquities with the outcropping crustal structures, particularly at LSCT, HRV, and WFM, where ϕ is almost orthogonal to the general N-S trend of the Appalachians.

Such an unambiguous discrepancy between the surface geologic fabric and values of ϕ is relatively rare [*Silver*, 1996]. It either implies that the mantle deformation of the lithosphere is effectively unrelated to the surface geology (crust/mantle decoupling) or that an asthenospheric component dominates the lithospheric contribution. In the context of an asthenospheric interpretation, this zone of E-W splitting would represent localized E-W flow in an asthenosphere, with either a thinned, or effectively isotropic lithosphere above. The evidence in favor of this interpretation comes from mantle tomography, and the distribution of igneous rocks. A recent shear wave tomography study of the North American continent [*Van der Lee*, 1995; S. Van der Lee and G. Nolet, The upper mantle *S* velocity structure of North America, submitted to *Journal of Geophysical Research*, 1996] reveals a major NW-SE trending low-velocity anomaly that extends from well out into the Atlantic, to several hundred kilometers inland and over a depth range of 80 to 250 km depth. Shown in Plate 1a and 1b are maps at 100 km and 200 km depth, respectively. This feature is more intense and localized at 100 km but is still present and extends farther to the west at 200 km depth, although with smaller amplitude. The close proximity of this anomaly to the stations exhibiting anomalous splitting suggests that the two are related. At a minimum, the low velocities suggest a lithospheric thickness of about 80 km for the near-coastal stations. This thickness requires very high intrinsic anisotropy to account for delay times larger than 1 s, and the participation of the asthenosphere for these stations must be seriously considered. This low-velocity feature is closely associated with igneous activity, following the trend of the New England seamount chain at sea and its on land extension [*Duncan*, 1984]. An extensive continental igneous domain (an area of 300 km by 400 km, see Plate 1a and 1b) termed the New England Quebec Province [*McHone and Butler*, 1984], which is similar in age to the seamounts just offshore (100-120 Ma), closely corresponds to both the locations of stations with anomalous splitting and the tomographic anomaly as well.

An alternative hypothesis for the anomalous splitting, is that it corresponds to fossil E-W trending lithospheric mantle

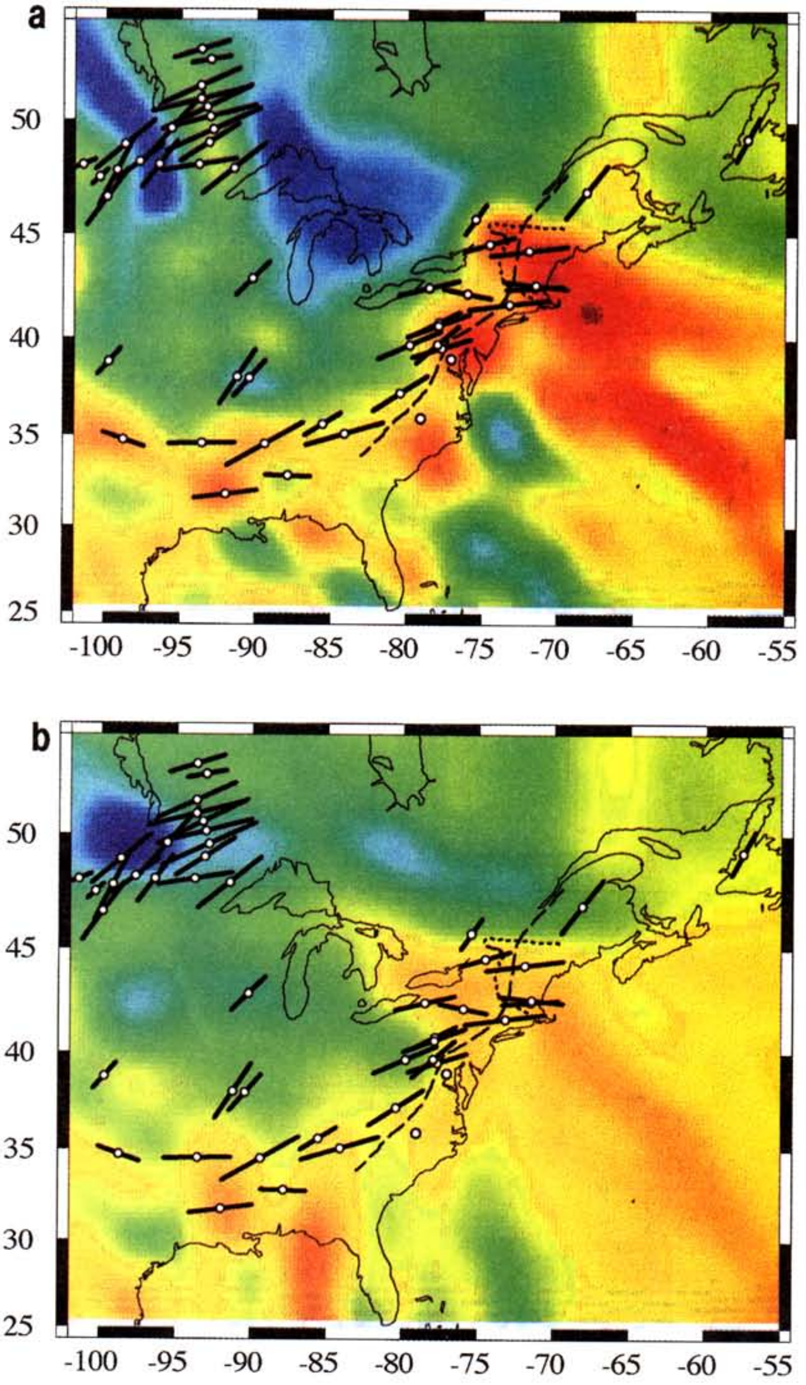
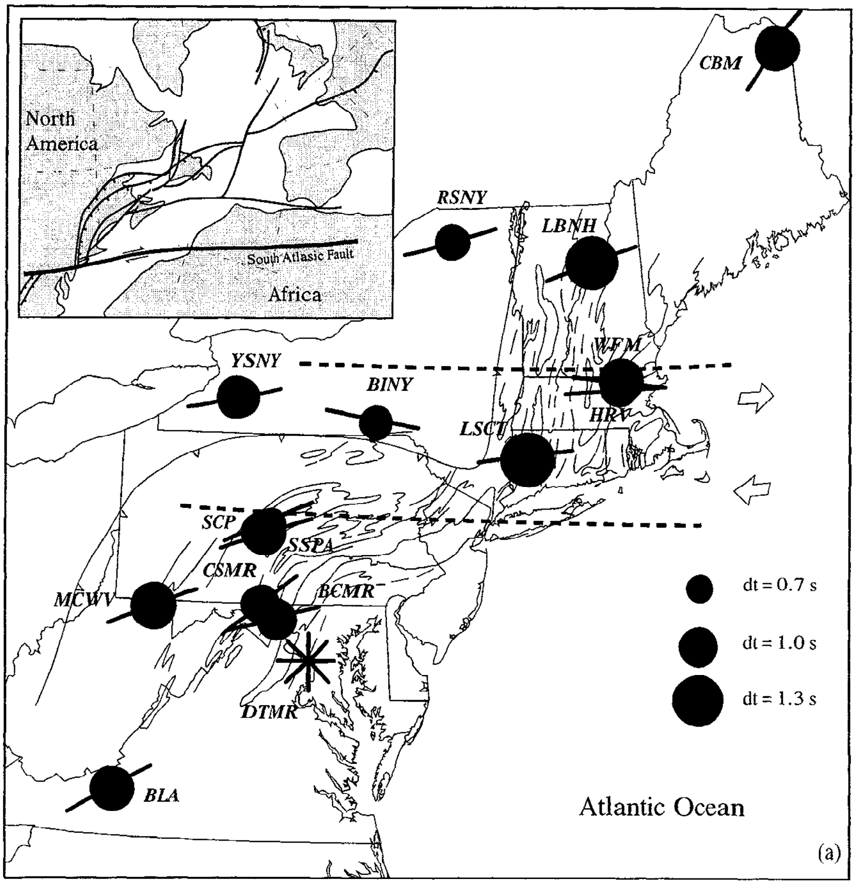


Plate 1. Splitting results where orientation of line gives fast polarization direction and the length of line is proportional to delay time. Open circles (without line) denote the absence of splitting. They are superimposed on a shear wave tomographic model of North America by S. *Van der Lee and G. Nolet* (submitted manuscript, 1996) at (a) 100 km and (b) 200 km depth. Blue and red colors denote regions of relatively fast and slow velocity respectively. In Plate 1a, full scale is 10%, while in Plate 1b it is 5%. These maps clearly show that the largest splitting are observed above the thickest cratonic root, suggesting the anisotropy is frozen in the continental root. The lowest velocity anomaly is a NW-SE trending feature that extends on land in New England, near where anomalous E-W trend of the fast polarization direction are found. This feature is most intense at 100 km depth but is still present at 200 km depth, although more diffuse and at lower amplitude. This region also possesses unusual igneous characteristics, namely the New England Quebec Province that is related to the New England Seamount Chain [*McHone and Butler*, 1984]. This zone is outlined in Plates 1a and 1b by the dotted line. The correspondence of anomalous splitting, low velocities and the presence of igneous activity, argues for localized asthenospheric component to the anomalous splitting. Also shown in dashed line is the western boundary of the Eastern North America Dolerite Province [*McHone and Butler*, 1984] that marks the inland influence of Atlantic rifting. Note that the stations without splitting in the western Appalachians are within this province, suggesting that the rifting has reduced anisotropic fabric produced by preceding orogenic events.



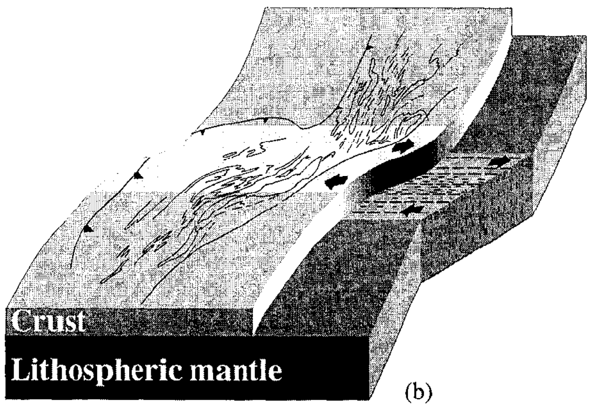


Figure 10. (a) Close view of the shear wave splitting in the New York area together with the main structural trends. This zone is characterized by a rotation of the crustal structures (the Pennsylvania promontory) that marks the boundary between the northern and the southern Appalachians. Splitting results at BINY, LSCT, HRV, and WFM show an anomalous E-W orientation of the fast shear wave, contrasting with the NE-SW to N-S orientation observed elsewhere in the Appalachians. This feature may be attributed to a forced flow in the flowing asthenosphere beneath this zone or to the presence of a paleo transform zone that was active during the Appalachian collision. If the source of the anisotropy is mainly related to a lithospheric structure, the roughly E-W orientation of ϕ on N-S crustal structures clearly imply a decoupling between the crust and the mantle. The inset is a schematic of pre-Atlantic Ocean opening reconstitution, modified from *Rast* [1989], showing the existence of a transcontinental strike-slip fault linking the South Atlasic fault to the Martic line, in the studied area. A possible interpretation of the E-W trend of the fast split shear wave in this area may be to consider that it corresponds to a frozen tectonic structure related to this compressive transform fault that worked during the North America-Africa collision.
(b) 3-D cartoon of the hypothetical structure that may explain the E-W anisotropy anomaly in the New York region. The deformation in the upper mantle during the Africa- North America collision could consist in a broad strike-slip zone, with vertical foliations (the dashed lines) and could be frozen since that time. A crust-mantle decoupling above this wide transcurrent fault in the lithospheric mantle is needed in order to be consistent with our observations.

deformation that has not pervasively deformed the surface rocks. One candidate for this deformation is a paleotranscurrent fault zone that accommodated relative motions between the northern and central Appalachians in the Hercynian orogenic system, during the North America-Africa collision (Figures 10a and 10b). The four stations BINY, LSCT, HRV, and WFM are located close to the boundary between the northern and southern Appalachians. This boundary also marks the northern limit of the "Pennsylvania salient" of the Appalachian belt, which probably results from the indentation of North America by the Reguibat Promontory of West Africa [*Vauchez et al.*, 1987] and was possibly prefigured by a reentrant of the initial rift formed during the Late Precambrian-Early Cambrian Gondwana break-up. A reconstitution of the North American, African, and European continents before the opening of the Atlantic [*Lefort and Van der Voo*, 1981], clearly shows that the Appalachian structural trend in the Pennsylvania area curves around the Reguibat Promontory and that the limit between the northern and central Appalachians fits a transcontinental fault zone that links the Martic Line in the Appalachians to the South Atlasic fault in Africa (Figure 10a and inset). From surface geology, gravity, and magnetic anomaly mapping, the boundary between the central and northern Appalachians does not appear as a major tectonic discontinuity [e.g., *Taylor*, 1989], except in the Connecticut area where geologic units terminate abruptly southward. In Pennsylvania, the Appalachian belt merely displays a substantial curvature of its structural trend and of gravity and magnetic anomalies from NNE to almost E-W. If the E-W trending fast polarization results from the fossil fabric of an orogen-transverse lithospheric shear zone, it implies that a crust-mantle decoupling occurred beneath this area, with the mantle deforming in a wide shear zone and the crust accommodating the relative displacement by a large-scale curvature and subsidiary faulting (see Figure 10b). The maximum width of the shear zone in the mantle remains problematic but could exceed 100 km in the lower lithosphere. An E-W polarization of the fast shear wave is also found at HRV and WFM and could be related to the same tectonic process. In this region, the crustal geologic structures also show a curvature from a N-S to an ENE trend that may have accommodated in the crust a relative displacement along a mantle shear zone.

The E-W orientation of the fast polarization direction is well explained by this hypothesis, based on petrophysical studies on how upper mantle minerals deform. These studies show that the fast split shear wave is polarized in a plane parallel to the foliation and that the obliquity between the olivine *a*-axes concentration (that marks the direction of shear) and the lineation (that marks the extension direction of finite strain) is small. Therefore, above a lithospheric transcurrent fault characterized by large-scale vertically foliated mantle, splitting delay time is expected to be maximized and the orientation of the fast shear wave should be parallel to the strike of the vertical foliation in the mantle [e.g., *Vauchez and Nicolas*, 1991].

Interpreting shear wave splitting as due to an E-W paleotransform fault within the mantle leads to several consequences: (1) From the distribution of stations and from Fresnel zone arguments, the width of the deformed strike-slip zone in the lithospheric mantle must be larger than 100 km. (2) The upper mantle anisotropy magnitude related to the strain localization in this transcurrent fault would have to be about 7 to 8% beneath LSCT for the 80-km-thick lithosphere inferred from

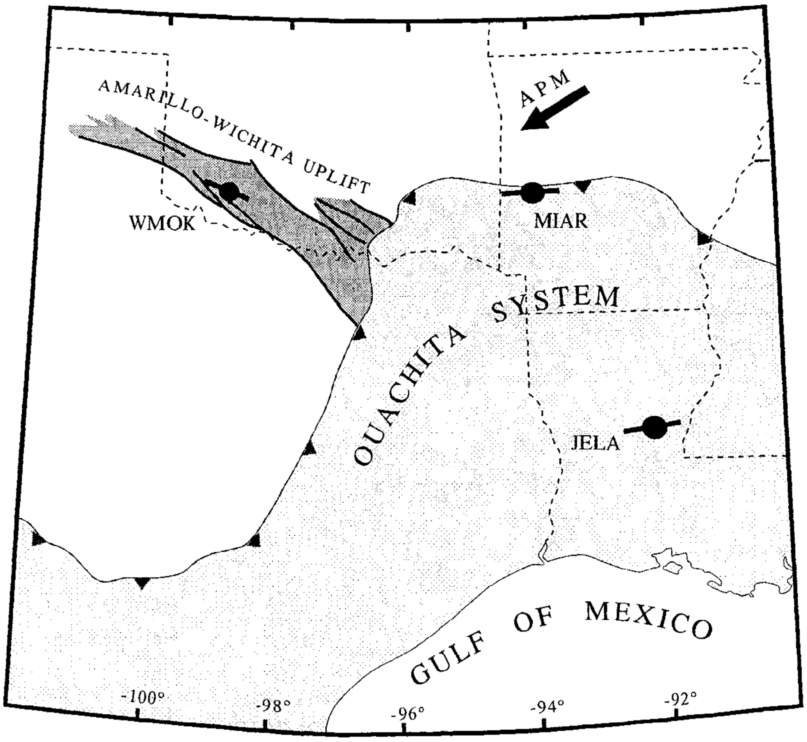


Figure 11. Schematic map displaying the main geologic domains and shear wave splitting results in the southern United States illustrating the parallelism between the orientation of the fast split shear wave measured at WMOK and crustal structures. The station lies on an aborted rift system, marked by a clear parallelism between the trend of the Wichita Mountains (N120°E), the magnetic anomaly and a very strong gravity anomaly oriented parallel to the rift, suggesting an important and pervasive deformation associated to this structure. Note the obliquity between the APM (N65°E) and the fast split shear wave at WMOK (N109°E), MIAR (N89°E) and JELA (N83°E).

the tomography. These are exceedingly large values (a value of 10% would be appropriate for single-crystal olivine), although occasionally such large values are found from mantle samples [*Ben Ismail et al.*, 1996]. (3) Finally, the near-orthogonal trends of surface geology and fast polarization direction would require decoupling between the mantle and the crustal components of the lithosphere during this collisional event.

In summary, this E-W trending anomaly could result from present-day E-W asthenospheric flow induced by an earlier thermal event associated with the New England Seamount chain or from a fossil lithospheric structure related to a paleotransform fault (or both). Distinguishing between the two is not possible with the current data set but could be done with a dense network of portable broadband seismic stations passing through this anomalous domain.

Influence of Preorogenic Rifting

Finally, there is one example where preorogenic rifting appears to dominate the contribution to mantle anisotropy. The station WMOK of southwestern Oklahoma exhibits an orientation of the fast split shear wave (N109°E) significantly oblique to the Grenville front (roughly E-W). This station is located in the Wichita Mountain aulacogen (see Figure 11), an aborted rift initiated in the Late Proterozoic-Early Cambrian during Gondwana breakup and that reworked the Grenville front. The Wichita Mountain trends WNW and is characterized by a large positive gravity anomaly [*Hanna et al.*, 1989]. Abundant basaltic magma intruded and partially melted the crust during rifting, generating a bimodal magmatism [*Gilbert and Denison*, 1993]. Finally, the rift was deformed and uplifted during the Ouachita orogeny. The fast polarization direction is parallel to the trend of the Wichita Mountains and the associated gravity anomaly. Although forced asthenospheric flow cannot be ruled out as an explanation for the splitting parameters of this one station, orogenic lithospheric deformation developed beneath the Wichita Mountains provides an equally good, if not better explanation. A possible explanation of mantle flow parallel to the rift walls has been developed by *Nicolas* [1993].

Conclusions

Teleseismic shear wave splitting has been observed at most stations located in the eastern United States. Combining these observations with other geophysical and geological arguments, we wish to point out the following conclusions:

Despite a dominant NE-SW orientation of the fast polarization direction, roughly parallel to the absolute motion of the North American plate, the splitting pattern defined from a large number of stations is rather complex and precludes an interpretation of the data set by simple asthenospheric flow.

The large-scale anisotropy pattern around the southern and eastern margins of stable North America consists of values of ϕ that trend E-W and NE-SW, respectively. These measurements are primarily within the Grenvillian domain and are locally parallel to the large-scale trends of the belt. This is compatible with the idea of fossil deformation from the Grenville orogeny. Alternatively, this pattern could be explained by asthenosphere flow that is deflected around the thick North American craton. However, in several places small-scale variations in splitting parameters show a good correlation with surface geology and therefore support a major geologically related lithospheric contribution to shear wave splitting.

The Atlantic rifting appears to be responsible for the absence of anisotropy for stations in the eastern Appalachians.

There is one anomalous area in which the seismic anisotropy clearly does not follow the surface geology. This means that tectonic information not visible from the surface can be inferred from shear wave splitting. In transition zone between the northern and central southern Appalachians, an E-W trend in the fast polarization direction is oblique to the Appalachian trend. We suggest two interpretations: (1) This is the result of local asthenospheric flow related to the onland extension of the New England seamounts or (2) it is due to lithospheric deformation associated with a transcontinental transform fault active during the Appalachian collision. The former interpretation implies that the seamount-related volcanism strongly perturbed the mantle structure and flow field, whereas the latter interpretation implies decoupling at the crust-mantle boundary during the Africa-America collision

The structure of the lithosphere associated with Proterozoic rifts may locally explain splitting parameters, suggesting that such mantle structures may be preserved in cratonic areas.

Continents result from a long and complex evolution involving periods of terrane accretion as well as periods of fragmentation. Moreover, continental plates usually involve old nuclei beneath which thick lithospheric roots have developed. Subsequent orogens usually wrap around these nuclei, and if the lithosphere and the asthenosphere are decoupled due to the current motion of the plate, the asthenosphere flow should be deflected around the root of the craton. In both cases the direction of fast shear wave polarization should parallel the boundary of the cratonic nucleus. This raises an ambiguity in the interpretation of the large scale anisotropic pattern. A detailed analysis of the systematics of the data set, namely, the small-scale variation in the splitting parameters, the good correlation between splitting delay times and lithospheric thicknesses, and the modification of the general pattern correlated with specific geological structures, supports a major contribution of correlation between delay times and the lithospheric thickness, and the modification of the general pattern correlated with specific geological structures supports a major contribution of lithospheric deformation.

Farther testing of these conclusions and resolution of the ambiguities noted above can be achieved by the collection of additional data that focus on particular regions with short-length-scale variations in anisotropic properties. These include areas such as the transition from "Grenvillian" to "cratonic" ϕ orientations in the south and the transition from the western to (weakly anisotropic) eastern Appalachians. Perhaps the most intriguing area for farther study is the anomaly located within the transition from north to central southern Appalachians. Regardless of the ultimate interpretation, this feature is reflecting a process that is only faintly visible at the surface.

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